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Impacts of land-use/land-cover changes on nutrient losses in agricultural catchment, southern Ethiopia

Hailu Gisha Kuma *, Fekadu Fufa Feyessa and Tamene Adugna Demissie

Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, P.O. Box 378, Jimma, Ethiopia
*Corresponding author. E-mail: hailugisha@yahoo.com

HGK, 0000-0001-5755-888X; FFF, 0000-0001-8974-0328; TAD, 0000-0001-6750-8819

ABSTRACT

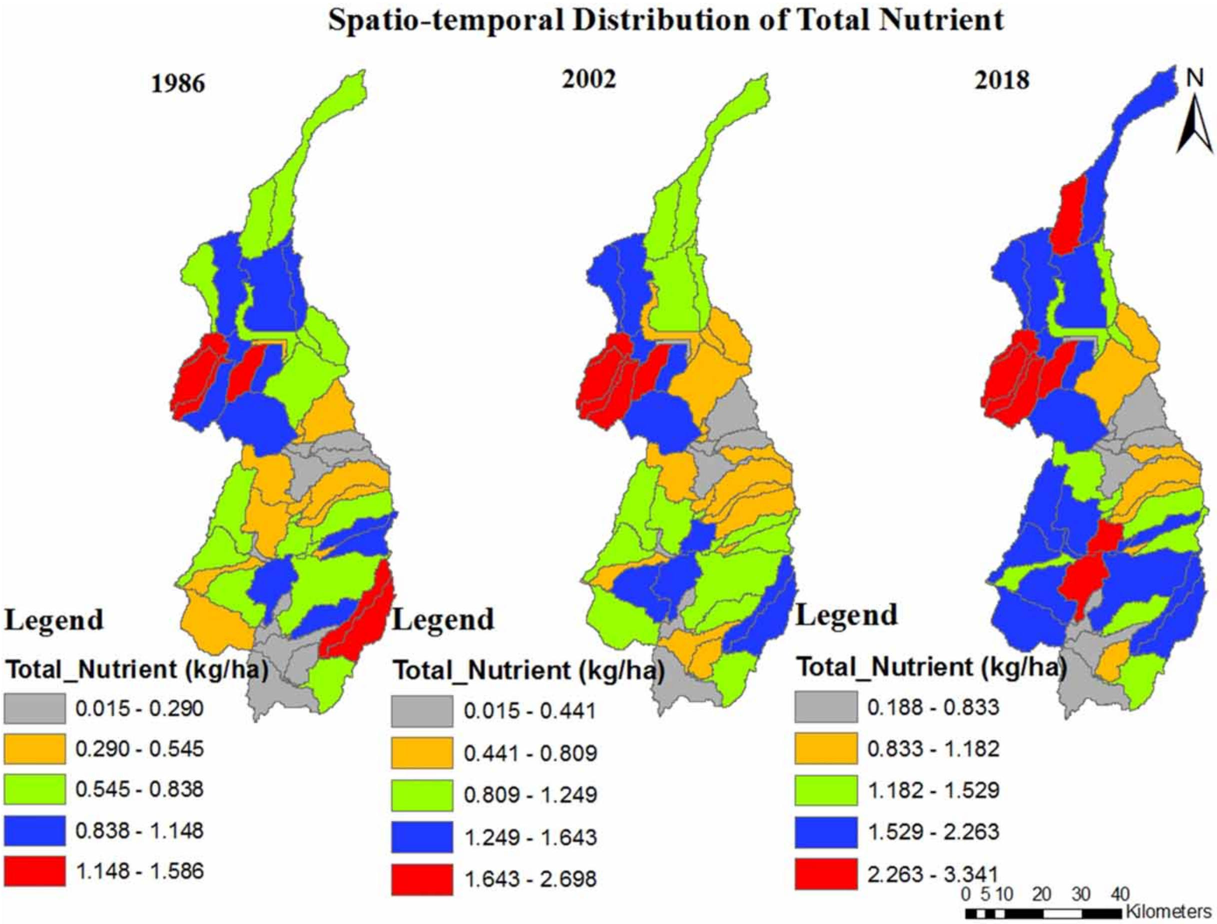
Assessing the impact of land-use/land-cover (LULC) change and nutrient loads on water systems is a key issue, where different water uses raise water-quality concerns. This study aimed to enumerate the extent of the LULC change from 1986 to 2018, its measurable impacts on nutrient losses and major pollution areas based on the SWAT in the Bilate catchment, southern Ethiopia. The sequential uncertainty fitting version two (SUFI-2) algorithm in SWAT-CUP was used in calibration and validation. Calibration and validation showed good agreement between observed and simulated values. Results showed that significant changes in nutrient loss occurred, following the direction of LULC changes between 1986–2002 and 2002–2018. The increase in agricultural land and built-up area accounted for 9.46% and 0.69% of the catchment area, respectively. The total phosphorus and nitrogen loads reached 2.52–1.27 kg/ha and 15.41–31.69 kg/ha between 1986–2002 and 2002–2018. Sub-basins 11, 14, 16, 17, 18 and 55 were the most important areas with nutrient pollution sources identified. The nutrient loads reduce water quality and fish productivity in Lake Abaya. The results of this study improved the understanding of nutrient loading from LULC changes and provided the required knowledge on integrating LULC and water-quality management.

Key words: Bilate catchment, LULC change, nutrient loss, SWAT model

HIGHLIGHTS

- The study employed the SWAT model and SUFI-2 algorithm.
- Spatio-temporal LULC changes were accompanied with varying nutrient losses.
- High-pollution-contributing sub-basins were identified.
- Nutrient losses follow the directions of LULC changes and surface runoff.

GRAPHICAL ABSTRACT



INTRODUCTION

Land-use/land-cover (LULC), climate, topography, soil properties, and spatial interactions and changes between these factors are responsible for changing catchment hydrology. Land-cover change has become a serious environmental concern at local, regional and global scales (Kumar *et al.* 2015). Changing land-cover affects hydrological processes by altering the rate of water infiltration and surface runoff (Javed *et al.* 2012). LULC changes and their interactions with hydrological processes are spatially and temporally dynamic (Blöschl & Sivapalan 1995). The distribution of land cover can have a significant impact on the hydrology of the catchment.

The hydrological processes vary in time and space due to changes in the LULC. The processes control the export of nutrients from the land surface to the water bodies. It is the variability of these hydrological processes that produces spatially and temporally flexible forms of nutrient transport (Stieglitz *et al.* 2003; Kleinman *et al.* 2006). Hydrological processes determine the transport of nutrients and the path of diffuse pollution (Crossman *et al.* 2014). Surface runoff and groundwater recharge are among the most important key components in the hydrological process that are closely related to LULC changes. LULC changes directly affect the surface runoff and groundwater recharge regime; they are also important factors in the movement of nutrients. Surface runoff and groundwater are the main pathways and nutrient losses, with surface runoff being substantial (Pfannerstill *et al.* 2014; Yao *et al.* 2021).

Arable land is the source of nutrient loads due to intensive agricultural activities such as the use of chemical fertilizers. These chemicals can be discharged from these areas into water bodies (Küstermann *et al.* 2010; Panagopoulos *et al.* 2011). Pollution of water bodies would result from the ever-increasing use of chemical fertilizers and manure. However, after 1990, with increasing fertilizer use in developing countries, freshwater pollution has increasingly become a pervasive problem (Baker *et al.* 2005; Singh & Craswell 2021). Chen *et al.* (2020) reported that in a heavily urbanized region, the northern Taihu Basin, China, an increased accumulation of nitrogen loads was observed between 1990 and 2017 as the built-up land area increased from 23.85% to 61.72% during this period. Water resources have been polluted by waste from many point and non-point sources. This causes the water value to drop as the water source cannot meet the increasing demand. Nutrients such as phosphorus and nitrogen are serious issues threatening water quality (Krysanova & Haberlandt 2002; Huang *et al.* 2009). Nutrient loads to water bodies cause water-quality degradation including toxic algal blooms and eutrophication, oxygen depletion, and fish death in river systems and lakes (Niraula *et al.* 2013; Xu 2013). Nutrients increase the biological productivity of surface waters by accelerating eutrophication and some health problems. For example, adverse reproductive outcomes and birth defects can be increased when nitrate is ingested (Ward *et al.* 2018); the symptoms of diarrhea, inflammation and infections of the gastrointestinal tract, protein intolerance, blue baby condition (Water 2019); impaired phosphorus balance can affect the musculoskeletal and cardiovascular systems and ultimately lead to an increase in morbidity and mortality in the affected patients (Razzaque 2011; Erem & Razzaque 2018).

Nutrient accumulations to water bodies vary on temporal scales. Quantifying nutrient weights and their variations between periods can provide useful information for nutrient reduction programs in watersheds (Chen *et al.* 2010; Du *et al.* 2014; Qiu *et al.* 2019). Simulation models are used to assess the impact of LULC change on water and nutrient loads (Lenhart *et al.* 2003; Pfannerstill *et al.* 2014). The temporal variation of the years and the spatial variation at the sub-basin level for the total nitrogen and phosphorus losses have been analysed with SWAT (Echegaray 2009; Huiliang *et al.* 2015; Shi & Huang 2021).

Studies conducted in different catchment areas showed that water resources are vulnerable to nutrient loads from agricultural fields, urban drainage systems and industrial centres. Tibebe *et al.* (2018) and Tibebe *et al.* (2020) studied the external nutrient loading and trophic status of Lake Ziway, in the Ethiopian Rift Valley. In their study, water samples from the Ziway River were collected over two years (2014 and 2015) and chemical analysis was determined for nutrient concentrations according to the American Public Health Association (APHA). A similar study by Lewoyehu *et al.* (2020) was performed on land management in terms of soil fertility and nutrient balance in the Kecha and Laguna watersheds in northern Ethiopia. In three studies, some water samples were collected and the nutrients estimated. In their studies, the contributions of LULC changes to nutrient losses and the nutrient sources were not indicated. Another study by Crossman *et al.* (2014) was performed on nutrient transport mechanisms that increase hydrochemical sensitivity to climate change in Lake Simcoe, southern Ontario. A study by Szatten & Habel (2020) investigated sediment and nutrient balance (total phosphorus) in the Brda River basin, using hydrological data. No direct correlation between nutrient losses and land-cover changes was indicated in their studies, but nutrient losses from climate change and the denudation process were indicated.

The Bilate catchment is located in the Rift Valley Basin of southern Ethiopia, which is home to a growing population. In the catchment area, there are districts with a population density of over 600 inhabitants per square kilometre (CSA 2013; Adugna 2014). Due to population growth, the hillsides and grazing lands in the catchment area have been converted into cultivated areas. As a result, reduction of natural vegetation, soil erosion, sediment and nutrient loading of water bodies have become common problems. In the catchment area, liquid and solid wastes from towns are washed away by surface runoff without treatment. The Bilate River and its tributaries flow into Lake Abaya. Abaya Lake is one of the economic sectors in which fish production and crocodile farming take place. The lake's fish resources are in danger of extinction due to increased use of fertilizers and a build-up of sediment eroded from the terrain (Keda 2021). The lake has been affected by years of deforestation, illegal farming without respecting the buffer zone, and similar practices. In addition, there is insufficient information on the effects of LULC and the impact of nutrient loss and load to the water body on water resources quality. The Bilate catchment has been subjected to severe LULC changes, chemical fertilizer use, and surface water pollution. Therefore, the study aims to investigate the spatial and temporal effects of LULC change on nutrient loss and loads into the surface water bodies through SWAT simulations in the Bilate catchment.

MATERIALS AND METHODS

Study area

The Bilate catchment covers 562,560 ha of land area and is located in southern Ethiopia (Figure 1). The catchment area spans different climate zones ranging from the highlands to the lowlands of the Rift Valley. The altitude ranges from 1,174 metres at Lake Abaya to 3,330 metres above sea level. It receives about 854–1,039 mm rainfall annually. The mean annual maximum

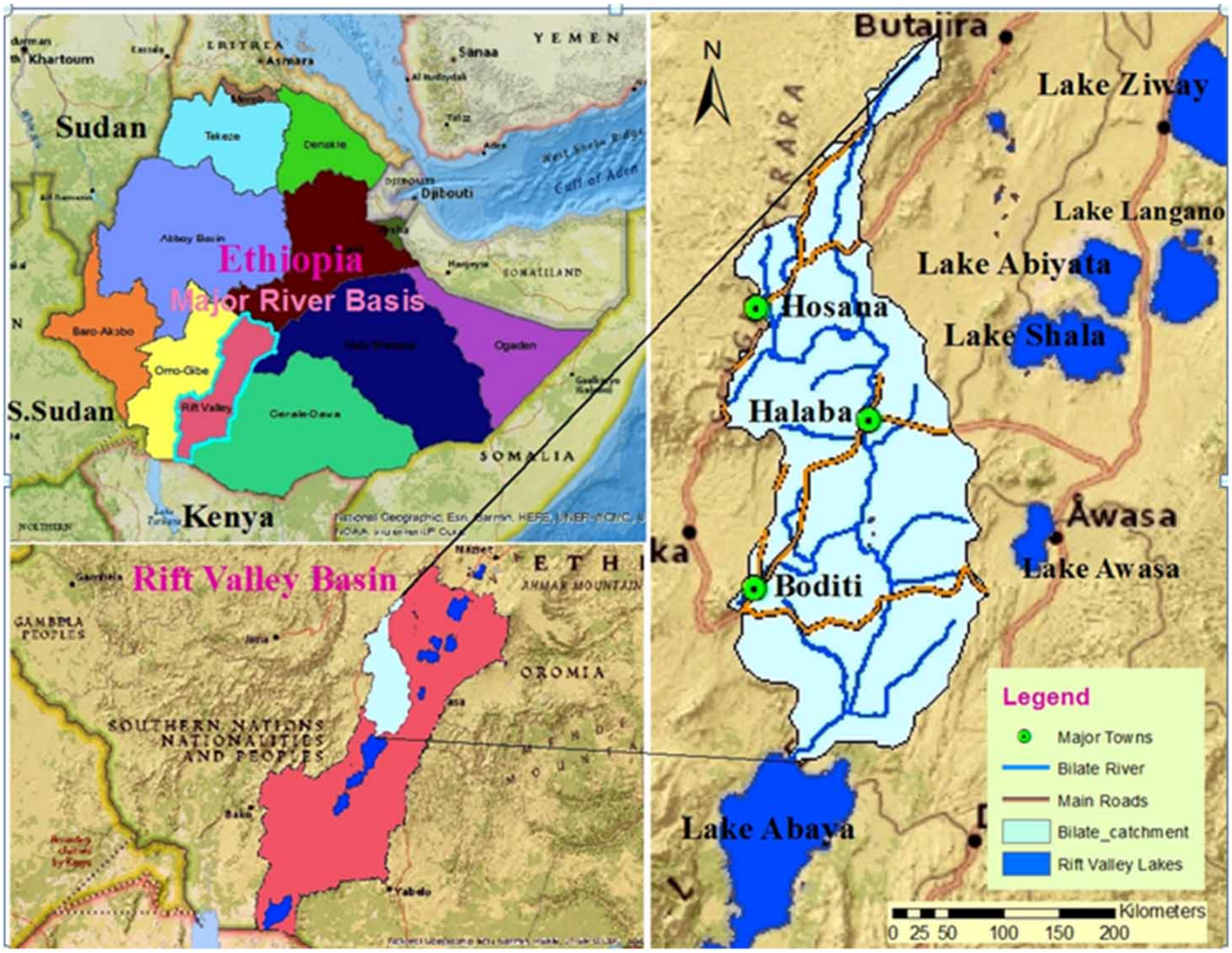


Figure 1 | Location map of Bilate catchment.

and minimum temperatures are 22.8–30.4 °C and 10.7–16.8 °C. Depending upon the landscape and topography, different types of indigenous and non-indigenous vegetation exist in the catchment. The high lands and middle areas are known for growing different crops such as wheat, clover, barley and teff. Farmers have intensive home gardens close to their homes, where they cultivate enset, avocado and coffee. Agroforestry and farmyard eucalyptus plantations are mostly practised to overcome the shortage of fuel and construction wood and to earn extra income. In the catchment, the Bilate River and its tributaries drain to Lake Abaya. Its maximum discharge is provided by most of the perennial streams from the western high lands of the catchment, and the eastern intermittent streams provide lesser amounts.

SWAT model database

The database for the SWAT model has been divided into two groups: spatial database and attribute database. All spatial databases have been converted to the projection coordinate system: WGS 1984 UTM Zone 37N. A 30 metre resolution DEM was downloaded from USGS at https://earthexplorer.usgs.gov. It was used to delineate the watershed into sub-basins and analyze the land surface drainage patterns of Bilate catchment. A 250 metre resolution of soil grids with comprehensive physical and chemical properties was taken from the Food and Agriculture Organization (FAO 2002). The dominant soils of the Bilate catchment are coded according to the SWAT database as Vitric Andosols (Vc25-3a-263), Pellic Vertisols (Nd3-1565), Chromic Vertisols (Nd17-1a-1554), Orthic Solonchaks (I-Lf-Rd-1264), Chromic Luvisols (Nh7-2-3c-853), Eutric Fluvisols (Fo94-2ab-556), Eutric Nitisols (Vc40-3a-956) and Dystric Nitisols (Vc39-3a-955). The less dominant soils are Eutric Regosols

(Fh1-3b-1156), Calcic Fluvisols (Fo91-2b-552), Calcaric Fluvisols (Fo90-2-3b-551), Luvic Phaeozems (Ao48-1a-1060) and Mollic Andosols (Vc14-3a-261).

Three LULC maps for 1986, 2002 and 2018 were developed by Kuma *et al.* (2021) were used. We used Landsat imagery from TM, ETM+ and OLI for 1986, 2002 and 2018, respectively, to assess LULC changes in the Bilate catchment. The identified LULC types are coded according to the SWAT database: water bodies (WATR), urban and built-up areas (URBN), grazing lands (PAST), cultivated areas (AGRC), scattered forest lands (FRST), and barren lands (BARR). The result of the LULC assessment showed an increase of water bodies, built-up areas, barren land and cultivated land rating at 0.19%, 0.69%, 1.36% and 9.46% of the catchment area, respectively. However, grazing and forest lands decreased by 3.46% and 8.52%, respectively, between 1986 and 2018. Daily rainfall, relative humidity, wind speed, radiation, and minimum and maximum temperature data from 1978 to 2017 were collected from the National Meteorological Service Agency of Ethiopia (NMSA 2019). Daily flow data of the Bilate River over the same period was obtained from the Ministry of Water, Irrigation and Energy of Ethiopia (MoWIE 2019). DEM, LULC maps, soil maps and meteorological data were used in SWAT simulation. The hydrological data were also used for calibration and validation.

METHODS

Hydrological model construction

In this study, the hydrological modelling approach using the SWAT model was employed. The physically-based and semi-distributed SWAT model used to assess the consequences of land use management follows on hydrologic routes that occur in catchment areas (Arnold *et al.* 1998). The SWAT model customises the water equilibrium line to mimic watershed hydrological partitioning (Neitsch *et al.* 2011). The hydrological equilibriums are imitated by the SWAT model with the equation:

$$SW_t = SW_o + \sum_{i=1}^{t} P_{\text{day}} - Q_{\text{surf}} - E_{\text{a}} - W_{\text{seep}} - Q_{\text{gw}}) \quad (1)$$

where SW_t is the last soil water amount (mm), SW_{o} is the first soil water amount on day i (mm), t is the time (days), P_{day} is the quantity of precipitation on day i (mm), Q_{surf} is the quantity of surface runoff on day i (mm), E_{a} is the quantity of evapotranspiration on day i (mm), W_{seep} is the quantity of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the quantity of return flow or base flow on day i (mm).

Arc SWAT was used to perform DEM image recognition, extract river networks, compute the catchment area and delineate the sub-basins. To create detailed drainage connections and Hydrologic Response Units (HRUs), a smaller area (5,000 ha) was allocated and an outlet defined. Established on the thresholds of soil type, slope divisions and LULC types set as 15%, 15% and 15%, the total catchment area was 562,560 ha, and the catchment was divided into 60 sub-basins and 451, 424 and 416 HRUs of 1986, 2002 and 2018 LULC, respectively.

Nutrient transport mechanism and simulation in SWAT

Nutrients enter water systems in three ways: water moving across the land surface as runoff; soil or sediment eroded by runoff; and water percolating into the land. During the movement of water in these three ways, it transports soluble nutrients: nutrients liquefied in the water; attached to the eroded soil; and moving in rainfall–runoff and leaching water (Baker *et al.* 2005). The SWAT model monitors five different pools of nitrogen (Ekanayake & Davie 2005) and six pools of phosphorus in the movement (Chaubey *et al.* 2006). Two pools are inorganic forms of nitrogen such as NO_3^- and NH_4^+ while the three pools are organic forms of nitrogen such as active organic nitrogen, stable organic nitrogen associated with humic substances and fresh organic nitrogen associated with the crop residues. Organic phosphorus is constituted from crop residue, microbial biomass and humic substances whereas mineral phosphorus is categorized into solution, active, and stable pools. Organic phosphorus residual mineralization and inorganic phosphorus fertilizer decomposition in the soil produce mineral phosphorus which constitutes $H_2PO_4^-$ and HPO_4^{-2}. Similarly, SWAT simulates the agricultural chemicals and sediment yields at various spatial and temporal scales in a catchment (Arnold & Fohrer 2005; Gassman *et al.* 2007). The SWAT model assesses the nutrient loading to the water systems by accounting for nutrients in runoff and percolating flow.

Table 1 | Flow-sensitive parameters and their fitted values

1986_LULC			2002_LULC			2018_LULC		
Parameter	Range	Fitted	Parameter	Range	Fitted	Parameter	Range	Fitted
CN2	35–98	37.6	CN2	35–98	37.6	CN2	35–98	37.69
SURLAG	0–12	4.47	GW_REVAP	0.02–0.2	0.15	SOL_AWC	0–1	0.25
ESCO	0–1	0.4735	CH-N2	0–1	0.18	SURLAG	0–12	6.03
ALPHA_BF	0–1	0.0085	SURLAG	0–12	4.47	GW_REVAP	0.02–0.2	0.14
EPCO	0–1	0.0205	GWQMN	0–1,000	473.5	SOL_Z	0–3,500	2,371.25
GW_DELAY	0–500	363.25	ESCO	0–1	0.02	ESCO	0–1	0.16
SOL_Z	0–3,500	659.75	ALPHA_BF	0–1	0.0085	CH-N2	0–1	0.62
GW_REVAP	0.02–0.2	0.119	RCHRG_DP	0–1	0.0145	GW_DELAY	0–500	121.25
RCHRG_DP	0–1	0.0145	GW_DELAY	0–500	363.25	CH_K2	0–500	381.25
CANMX	0–100	87.15	CH_K2	0–500	275.25	CANMX	0–100	88.25
CH_K2	0–500	275.25	CANMX	0–100	55.04	SOL_K	0–2,000	1,045.0
REVAPMN	0–500	367.75	REVAPMN	0–500	435.75	EPCO	0–1	0.55

Parameter sensitivity analysis, model calibration and validation

Iterative modelling was performed using the global sensitivity analysis tool in SWAT-CUP to select 12 parameters associated with runoff and nutrient movement (Table 1). This method has been recognized mainly for deciding the most sensitive parameters for model calibration using One-factor-At-a-Time (LH-OAT) (Ma *et al.* 2000; Lenhart *et al.* 2002; Griensven *et al.* 2006). The SUFI-2 algorithm set in SWAT-CUP was used during model calibration and validation (Abbaspour *et al.* 2015). Calibration is the adjustment of parameters within the proposed ranges to improve the simulated output so that it matches with observed data. Validation is testing the calibrated parameters against an independent set of observed data with no further changes to parameters. The monthly flows of Bilate River from 1978 to 2017 were used for calibration and validation.

Model performance evaluation

The Nash–Sutcliffe simulation efficiency (NSE) and the coefficient of determination (R^2) were chosen as indices for evaluating the model (Nash & Sutcliffe 1970). R^2 reflects the relationship between the replicated and observed data that can be elucidated by the model. The values range from 0 to 1 and the closer the value is to 1, the higher the alignment is between the simulated and measured flows, given by the equation:

$$R^2 = \frac{\left(\sum [Qsi - Qsi_{\mathrm{av}}][Qob - Qob_{\mathrm{av}}]\right)^2}{\sum [Qsi - Qsi_{\mathrm{av}}]^2 \sum [Qob - Qob_{\mathrm{av}}]^2} \quad (2)$$

where Qob is the observed value, Qob_{av} is the average measured value, Qsi is the predicted value, and Qsi_{av} is the average predicted value.

The Nash–Sutcliffe simulation efficiency (NSE) reflects the overall efficiency of model simulation. The closer the value is to 1, the better the model simulation fits. The fit between the observed and simulated data is determined using the equation:

$$NSE = 1 - \frac{\sum (Qob - Qsi)^2}{\sum (Qob - Qob_{\mathrm{av}})^2} \quad (3)$$

where Qob is the measured value, Qob_{av} is the average measured value, and Qsi is the predicted value.

The simulated value of a model is a better predictor and viewed as acceptable performance, once the values of R^2 and NSE are greater than 0.6 and 0.5, respectively (Santhi *et al.* 2001). The quality of calibration and forecast doubt is judged founded on the nearness of the *p*-factor to 100% and *r*-factor to 1 (Talebizadeh *et al.* 2009; Luo *et al.* 2014). The *p*-factor is all observations bracketed by the forecast doubt and the *r*-factor is the accomplishment of a rather small doubt band.

RESULTS AND DISCUSSION

Sensitivity analysis

The sensitivity examination of Bilate catchment by SWAT used 12 parameters. In the global sensitivity examination, a multiple regression system was used against the Nash–Sutcliffe objective function. The twelve parameters were sensitive with relative sensitivity values, for example, runoff curve amount to moisture condition II (CN2), groundwater 'revap' coefficient (GW-REVAP), effective hydraulic conductivity in the main passage (CH-K2), groundwater delay (GW-DELAY), deep aquifer filtration division (RCHRG_DP), baseflow recession constant (ALPHA-BF), the minimum distance of water in the thin aquifer for 'revap' (REVAPMN), soil evaporation compensation factor (ESCO), minimum depth of water in the thin aquifer required for return flow (GWQMN), plant uptake compensation factor (EPCO), surface runoff delay coefficient (SURLAG), available water capacity of the soil layer (SOL-AWC), maximum canopy storage (CANMX), Manning's '*n*' value for the main channel (CH-N2) and effective hydraulic conductivity in main conduit alluvium (SOL-K). These sensitive parameters are considered to have a high effect on Bilate River flow during calibration and validation in the SWAT-CUP. Table 1 shows highly sensitive parameters selected for modelling river flow and their fitted values.

The assessment of sensitive parameters was measured using the global sensitivity analysis tool. The sensitive parameters were chosen on the basis that the *t*-stat values are more sensitive to larger absolute *t*-stat values and *p*-values are closer to zero. The sensitivity results are with *t*-stat of 6.33–17.49, −6.12 to −14.34, and 3.32 to 27.35, respectively in 1986, 2002 and 2018. The sensitivity results are with a *p*-value of 0 in the three periods.

Flow calibration and validation

Calibration and validation were performed using Bilate River flow at the Halaba gauging station. The periods 1980–1988, 1993–2001 and 2009–2017 were used for flow calibration and validation. LULC maps of 1986, 2002 and 2018 were used in the simulation in the three periods. Flow calibration and validation were performed monthly. In each period, six years were used for calibration and three years for validation. The hydrographs were derived to examine the observed and simulated flow values for calibration and validation for each LULC map (Figure 2). In the simulations, the three LULC maps showed that the simulated flow agrees well with the measured flow. Both calibration and validation show that the SWAT model has achieved relatively good agreement between observations and simulations.

Model performance evaluation

The association of simulated and observed flow values during validation and calibration showed that the SWAT model can capture the river flow in the catchment. The agreement was achieved with R^2 and ENS values greater than 0.6 and 0.5. The achievement of the *r*-factor close to 1 is a rather small uncertainty band, and the *p*-factor to 100%, i.e all observations are bracketed by the prediction uncertainty (Hornberger & Spear 1981). The R^2, ENS, *p*-factor and *r*-factor of the flows for calibration and validation are shown in Table 2.

SWAT model calibration and validation results of the Bilate River are in line with other studies in different catchments. For example, the calibration and validation of stream flow on the Chinese Loess Plateau (Shi & Huang 2021); Ebro River Basin, Algeria River Basin (Epelde *et al.* 2015); and North River Watershed, China (Huang *et al.* 2013) were performed using the SWAT model. In their performance evaluations, the agreements for NSE and R^2 ranged from 0.83 to 0.95 during calibration, and from 0.58 to 0.95 during validation.

LULC changes and simulated nutrient losses in Bilate catchment

There were significant changes in the LULC in the Bilate catchment from 1986 to 2002 and from 2002 to 2018. Built-up areas, water bodies, cultivated land and barren land have increased, while forest and grazing lands have decreased between 1986 and 2018. LULC changes and nutrient losses are closely related in the catchments. A study by Li *et al.* (2021) agrees with this assessment: nutrient losses are related to land use, the rainfall–runoff process and agricultural production systems. The impacts of LULC changes on nutrient losses were substantiated by Delkash *et al.* (2018) and Sharpley *et al.* (2003).

Three SWAT simulations were performed to show the effect of LULC changes on nutrient losses. The nutrient losses such as nitrogen in surface runoff (NSURQ), nitrogen in lateral flow (NLATQ), nitrogen in groundwater (NGW), organic nitrogen

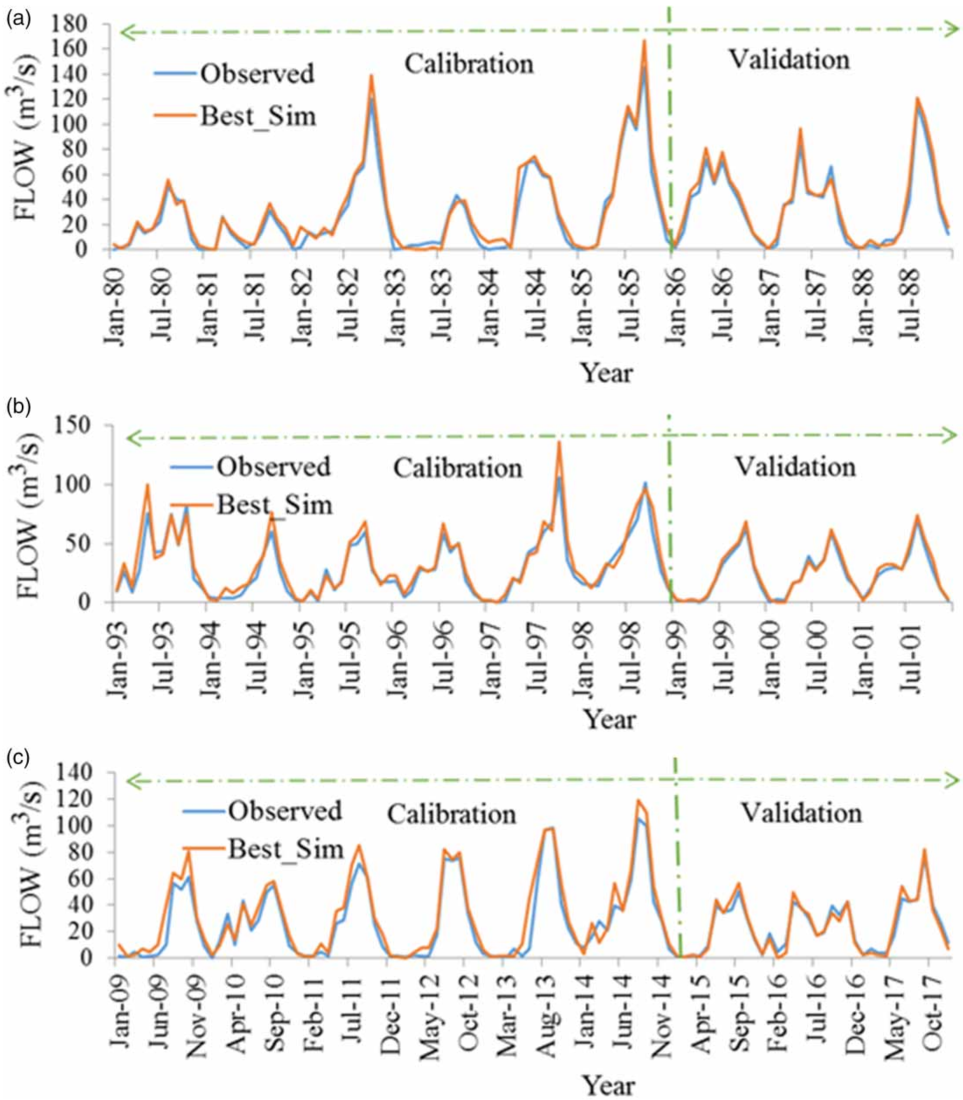


Figure 2 | Observed and simulated Bilate River flow for calibration and validation of (a) 1986 LULC, (b) 2002 LULC, and (c) 2018 LULC.

(ORGN), soluble phosphorus in surface runoff (SOLP), organic phosphorus in sediment (ORGP), and mineral phosphorus in sediment (SEDP) were quantified. The simulated nutrient losses from 1986 to 2002 and 2002 to 2018 due to LULC changes were enumerated and are shown in Tables 3 and 4.

The annual average nitrogen loss in surface runoff increased by 3.63–5.25 kg N/ha in 1986–2002 and 2002–2018, respectively. Similarly, the annual average losses of nitrogen transport in lateral flow and groundwater increased by 0.47–17.93 kg/ha,

Table 2 | Statistical values of R^2, ENS, p-factor and r-factor

	Calibration			Validation		
Parameter	**1986_LULC**	**2002_LULC**	**2018_LULC**	**1986_LULC**	**2002_LULC**	**2018_LULC**
R^2	0.73	0.73	0.79	0.73	0.75	0.82
ENS	0.67	0.69	0.75	0.68	0.71	0.75
p-factor	0.81	0.81	0.82	0.81	0.82	0.83
r-factor	0.73	0.72	0.75	0.74	0.73	0.75

Table 3 | Annual average phosphorus loss in Bilate catchment

LULC	SOLP (kg/ha)	ORGP (kg/ha)	SEDP (kg/ha)	Total P (kg/ha)
1986	0.31	3.46	3.60	7.37
2002	0.26	4.67	4.96	9.89
2018	0.33	5.33	5.50	11.16

SOLP=Soluble P; ORGP=Organic P; and SEDP=Mineral P.

Table 4 | Annual average nitrogen loss in Bilate catchment

LULC	N runoff (kg/ha)	N lateral flow (kg/ha)	N groundwater (kg/ha)	Organic N (kg/ha)	Total N (kg/ha)
1986	3.41	1.10	1.04	26.82	32.37
2002	7.05	1.57	1.07	38.19	47.78
2018	12.29	19.50	1.97	45.71	79.47

Nitrogen=inorganic nitrogen (NH_4^+, NO_3^-) and organic nitrogen (active, stable and fresh).

and 0.03–0.90 kg/ha in the periods. The annual average phosphorus loss in surface runoff was reduced by 0.06 kg P/ha from 1986 to 2002 and increased by 0.07 kg P/ha between 2002 and 2018. In addition, the annual average losses of organic and mineral phosphorus in the sediment increased by 1.21–0.66 kg P/ha and 1.36–0.54 kg P/ha in the two periods, respectively. The effects of LULC on average annual phosphorus losses are shown in Table 3. The nutrient load increment from 1986 to 2002 and 2002 to 2018 was attributed to an increase in the cultivation of sloppy lands, built-up areas and inorganic fertilizers use.

Soluble organic and mineral phosphorus bound to the sediment is transported from the catchment to the reach by surface runoff during the time step. The output intensity of total phosphorus reached 2.52 and 1.27 kg/ha for the periods between 1986 and 2002 and between 2002 and 2018, respectively. The effects of LULC on average annual nitrogen losses are shown in Table 4.

The output intensity of total nitrogen is increased, reaching 15.41 and 31.69 kg/ha for 1986–2002 and 2002–2018, respectively. This result agrees with a study by Bussi *et al.* (2021), who reported that the nutrient loads are expected to increase 15%–20% (nitrogen) and 30%–40% (phosphorus) in the future. An increase in the output intensity of phosphorus and nitrogen is closely linked to the nutrient movement and pollution of water bodies. The output intensity of these nutrients is related to the average annual surface runoff simulated by the SWAT in 1986, 2002 and 2018, which was 640.48, 659.86 and 671.95 mm/year, respectively. Therefore, increases in surface runoff have increased nutrient loads over the three periods. This shows that nutrient loads into the reaches follow the direction of surface runoff and LULC changes in the catchment. Studies conducted in different catchments are consistent with these results (Kebede *et al.* 2019; Chen *et al.* 2020; Szatten & Habel 2020; Li *et al.* 2021).

The spatio-temporal distribution of nutrient loads under LULC changes is shown in Figure 3. The SWAT model showed that total phosphorus and nitrogen loads in the upstream areas are high in the three time-periods. In the upstream areas, both elevation and surface runoff were higher than in the middle and downstream areas. In the downstream areas, a significant reduction in total phosphorus and nitrogen loads was observed due to the topography of the catchment area. Also, the total phosphorus and nitrogen loads downstream in the southeast and west are high because the areas are sloppy.

Sub-basin contribution to nutrient loads

The spatio-temporal distribution of the total phosphorus and nitrogen loading of the Bilate catchment is shown in Figure 3. The sub-basins with large pollution loads are distributed in the Bilate River and its tributaries. The intensity of total phosphorus loading reached 0.012–0.272, 0.001–0.418 and 0.021–0.358 kg/ha for 1986, 2002 and 2018, respectively. Sub-basins 14, 17 and 55 were heavily polluted in 1986; the total phosphorus load was between 0.235 and 0.272 kg/ha (Figures 3 and 4), while in 1986 sub-basins 25, 26, 27 and 58 were less polluted, and the total phosphorus load was between 0.012 and 0.035 kg/ha. In 2002 sub-basins 11, 14, 16, 17 and 18 were heavily polluted; the total phosphorus load was between 0.323 and 0.418 kg/ha. Sub-basins 48 and 58, however, made a smaller contribution; the total phosphorus load was between

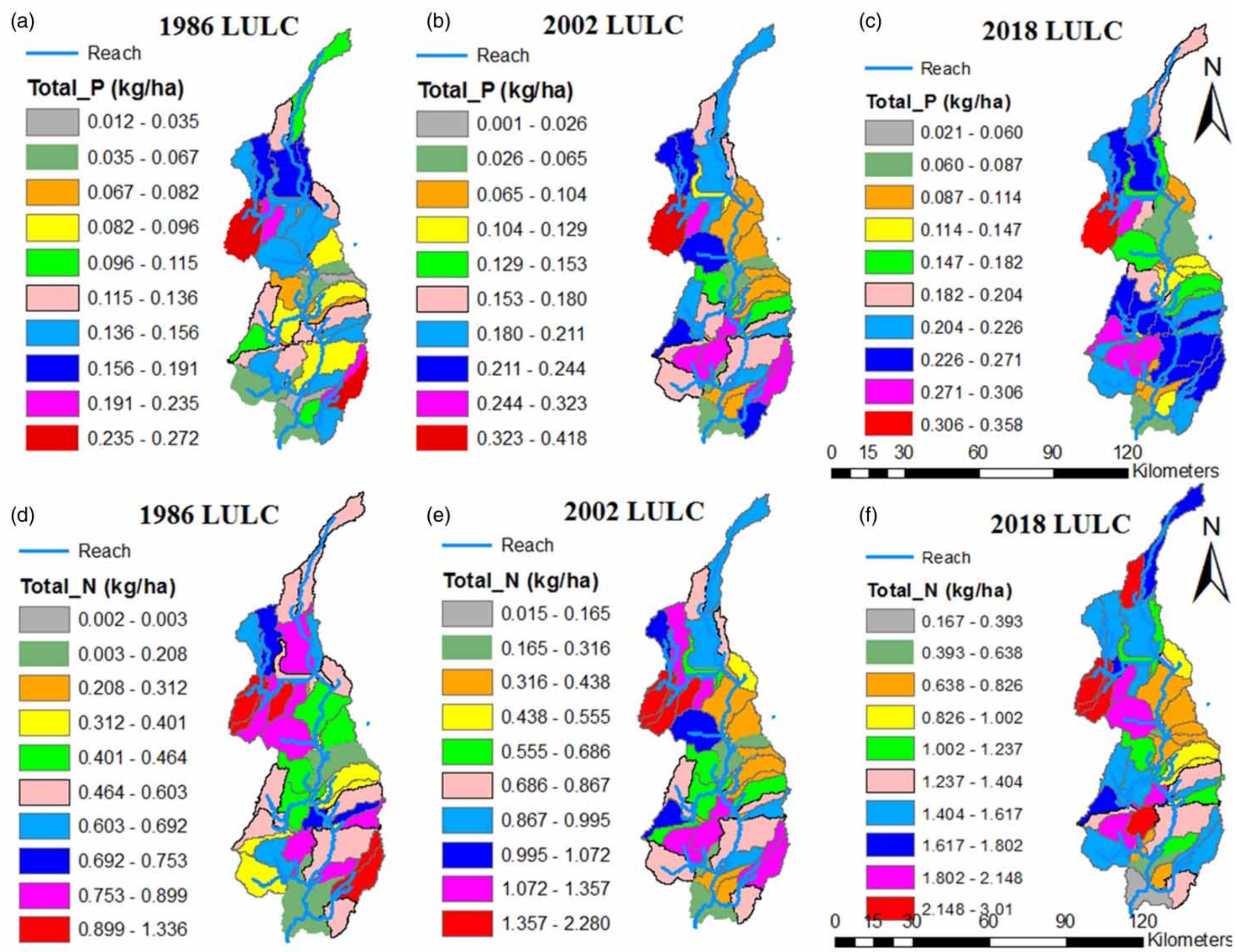


Figure 3 | Spatio-temporal distribution of total phosphorus loss (a–c) and total nitrogen loss (d–f) of Bilate catchment in 1986, 2002 and 2018.

0.001 and 0.026 kg/ha. Similarly, in 2018, sub-basins 14 16, 17, 18 and 47 were heavily polluted and sub-basins 5, 9, 22 and 58 were less polluted, and their total phosphorus loads were in the range of 0.306–0.358 kg/ha and 0.021–0.060 kg/ha.

The intensity of total nitrogen pollution reached 0.002–1.336 kg/ha, 0.015–2.280 kg/ha and 0.167–3.010 kg/ha for the years 1986, 2002 and 2018, respectively. In 1986 sub-basins 11, 14, 16 and 17 were high nitrogen load contributors while sub-basin 9 was less. In 2002 sub-basins 11, 14, 16, 17 and 18 were high nitrogen load contributors and sub-basin 9 contributed less. In addition, sub-basins 2, 14, 16, 17, 18 and 46 were high nitrogen load contributors and sub-basin 9 was less in 2018. The sub-basins of the catchment are shown in Figure 4.

Effects of nutrient loads in Lake Abaya

The nutrients from the Bilate catchment were transported to Lake Abaya (Figure 1). This shows that the lake habitat has been affected due to the increasing nutrient load. Likewise, Keda (2021) suggested considering Lake Abaya as the fish population is declining. The reduction in the fish population in the lake and other lakes in the Rift Valley Basin has been noted. For example, a study by Sime (2015) in Lake Hawassa observed that tilapia catches had decreased from 25–30 fish/net, and in 2015 the catch was five fish/net. Similarly, Kamaylo *et al.* (2021), reported that the previous total catch of tilapia was reduced from 126,306 kg/year to 42,205 kg/year in 2021 in Lake Abaya. In addition, Vijverberg *et al.* (2012) conveyed that fish productivity was higher in the past than in their study, because of high sediment load, overfishing and degradation of habitats in Ethiopian lakes. Fishing is an alternative means to achieve food security in Ethiopia (Kebede *et al.* 2017). Due attention should be given to Lake Abaya to increase the fish population and maintain food security.

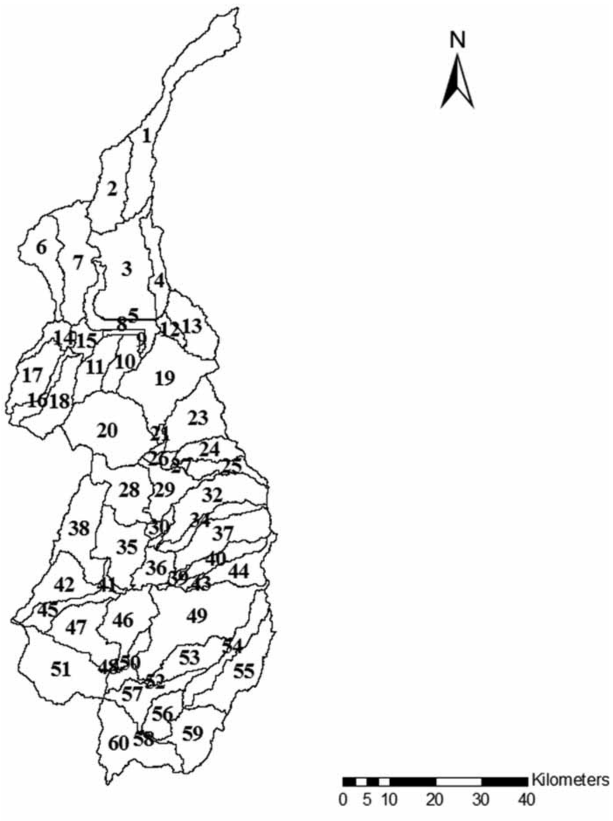


Figure 4 | Sub-basins of Bilate catchment area.

Sources of nutrient pollution in Bilate catchment

The main agricultural methods in the catchment area are diversified agriculture, in which both crop and livestock production are integrated. Farmers are using chemical fertilizers to improve crop production and the amount of fertilizer applied is increasing year by year. In Ethiopia, the amount of fertilizers used for the production of important crops increased in the period 1995–2004 (Endale 2011); fertilizer imports increased from 440,000 tons in 2008 to about 890,000 tons in 2012 (Rashid *et al.* 2013); and fertilizer consumption increased from 0.4 kg/ha to 36.2 kg/ha between 1986 and 2018, increasing at an average annual rate of 16.25% (https://knoema.com/atlas). Similarly, fertilizer use increased between 1991 and 1995 from 110,000 (21 kg/ha) to 300,000 (35 kg/ha) in 1999 (World Bank 2006).

The use of fertilizers increased nutrient loads to the water bodies due to rainfall–runoff. The impact of fertilizers and other sources amplifies water body contamination (Bijay-Sigh & Craswell 2021). Consequently, the fish resources of Lake Abaya are subject to destruction due to increased use of fertilizers applied in nearby agricultural areas and sediments eroded from the terrain (Golubtsov & Habteselassie 2010). In addition, Teffera *et al.* (2019), supposed that conservation programs should focus on reducing sediment inflow from the other catchments into Lake Abaya, in which the nutrient concentrations were higher during the wet seasons. The runoff increased nutrient loading of the water bodies and then Lake Abaya. In addition, nutrient deposition reduces water quality and fish productivity in Lake Abaya.

In the Bilate catchment area, urban and built-up areas grew by 0.69% between 1986 and 2018. As a result, a significant amount of untreated waste was released into the environment without treatment and was washed away through persistent runoff. This agrees with studies by Du *et al.* (2014) and Delkash *et al.* (2018), who reported that urban areas usually enhance nutrient concentrations in water bodies. Also, this result agrees with Kuma *et al.* (2021), who reported that runoff could increase nutrients in surface water bodies due to an increase in agricultural lands and urban and built-up areas.

CONCLUSION

The study investigated the spatio-temporal effects of LULC changes on nutrient losses in the Bilate catchment in southern Ethiopia. The database was created for SWAT model simulations for 1986, 2002, and 2018. Between 1986 and 2018, the average annual total phosphorus and nitrogen loads increased by 3.79 and 47.10 kg/ha, respectively. The observed total phosphorus and nitrogen output intensities of sub-basins were in the range of 0.235–0.418 kg/ha and 0.899–3.01 kg/ha, respectively. Sub-basins 2, 11, 14, 16, 17, 18, 36, 43, 47, 54 and 55 are the main source areas for phosphorus and nitrogen pollution, and the outputs of total phosphorus and nitrogen were very high. The catchment's agricultural lands, as well as its urban and built-up areas, were major sources of phosphorus and nitrogen pollution. Furthermore, LULC patterns and the climate play a role in the amount of phosphorus and nitrogen pollution in the water. Overall, the findings emphasize the importance of advocating for comprehensive and long-term management strategies to combat nutrient loads in the Bilate catchment.

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CONFILICT OF INTEREST

The authors declared that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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